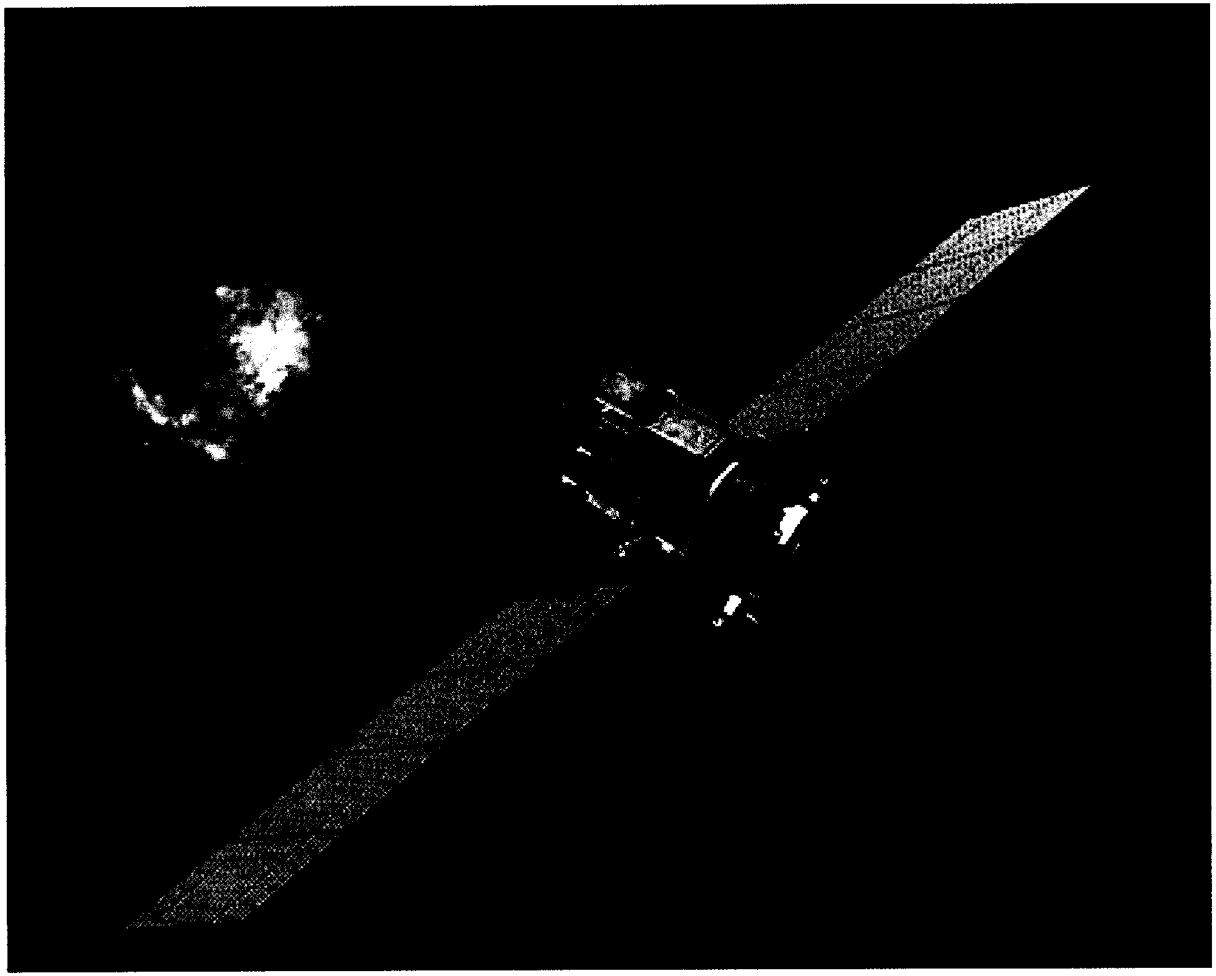
31st Annual Meeting of the Division for Planetary Sciences of the America Astronomical Society, Padua, Italy



David H. Lehman, Jet Propulsion Laboratory

October 10-15, 1999

Agenda

- New Millennium program and Deep Space 1 project
- Technology payload
- Mission
- Technology benefit example
- Braille encounter summary
- Questions/discussion
- Fly back to Los Angeles
- Stop at store on way home
  - Milk
  - Bread
  - Toothbrush
  - Xenon
  - Bananas

New Millennium Program

Objective:

- Flight validate advanced technologies to help enable NASA's vision of space and Earth science programs.

Technology selection criteria:

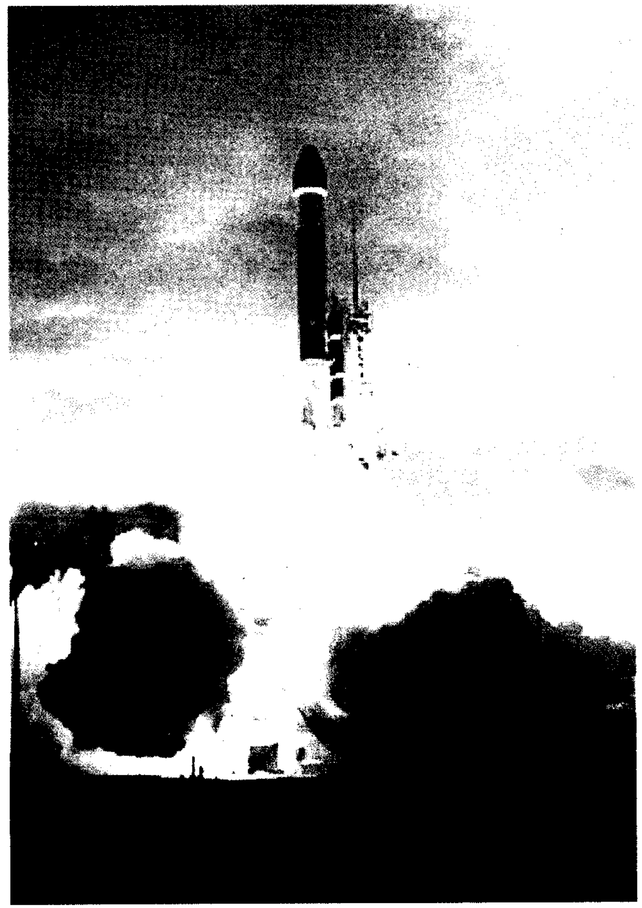
- Present a high risk to the first user and require in-flight validation.
- Reduce cost and risk of future programs.
- Represent a significant improvement over state of the art.

Technology validation:

- Assess the applicability of the technology product to those programs.
  - Elucidating the limitations of an advanced technology is valuable.
- Diagnose in-flight anomalies.

Deep Space 1 Project

- Primary objective
  - Flight validate advanced technologies selected by the New Millennium program
- Launched on October 24, 1998
  - 39 months from concept initiation
  - 26 months from formulation of level-1 requirements.
- Primary mission ended on September 26, 1999
- Extended mission devoted to encounters in 2001 with Comet/Asteroid Wilson-Harrington and Comet Borrelly



Boeing Delta 7326 launch vehicle lifts off with DS1 onboard

Technology Payload

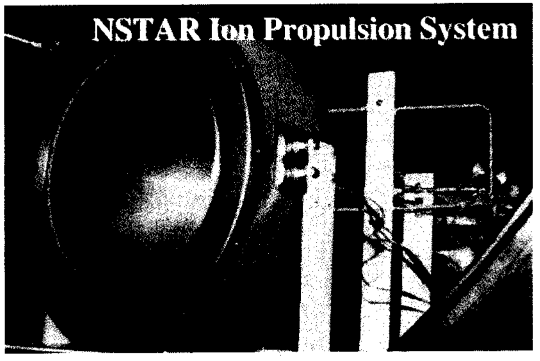
Technology Description	***Technology Suppliers***	***Funding Sources***
ION Propulsion System	Hughes, Moog, LeRC, JPL	NASA, Moog, Hughes
SCARLET Solar Concentrator Array	AEC-Able, Tecstar	BMDO, NASA
Small Deep Space Transponder	Motorola	NASA, Motorola
Ka-Band Solid State Power Amplifier	Lockheed Martin (LM), JPL	NASA, Lockheed Martin
Autonomous Remote Agent Architecture	CMU, TRW, JPL, ARC	NASA
Autonomous Onboard Optical Navigation	JPL	NASA
Beacon Monitor Operations	JPL, Univ. of Colorado at Boulder	NASA
Miniature Imaging Camera Spectrometer	SSG, Rockwell, Univ. of Arizona, JPL	NASA, SSG
Miniature ION and Electron Spectrometer	SwRI, LANL	NASA, SWRI
Low Power Electronics Experiment	Georgia Tech., USC, MIT Lincoln Lab	NASA
Power Actuation and Switching Module	LM	NASA, Lockheed Martin
Multi-Fuctional Structures	AF/PL, LM	AF/PL, LM

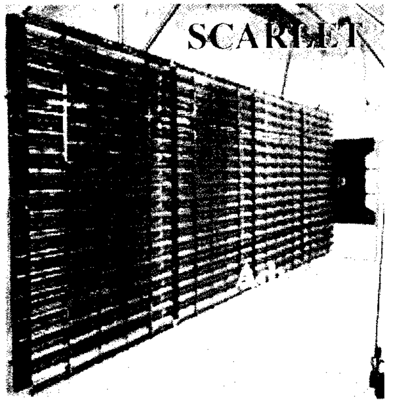
Mission Success Criteria

Status	*Item*
	1) Demonstrate the in-space flight operations and quantify the performance of the following 5 advanced technologies:
Complete	• Solar Electric Propulsion
Complete	• Scarlet Solar Concentrator Arrays
Complete	• Small Deep Space Transponder
Complete	• Miniature Camera and Imaging Spectrometer
Complete	• Autonomous Navigation
	and 3 of the 6 following advanced technologies:
Complete	• Beacon Monitor Operations
Complete	• Autonomous Remote Agent
Complete	• Ka-band Solid State Power Amplifier
Complete	• Low Power Electronics
Complete	• Multifunctional Structure [+ Plasma Experiment for Planetary Exploration (PEPE)]
Complete	• Power Actuation and Switching Module
Analysis and dissemination in progress	2) Acquire the data necessary to quantify the performance of these advanced technologies by September 30, 1999. Analyze these data and disseminate the results to interested organizations/parties by March 1, 2000.
Complete	3) Utilize the on-board Solar Electric Propulsion (SEP) to propel the DS1 spacecraft on a trajectory that will encounter a near-Earth asteroid in FY 1999.
Complete	4) Assess the interaction of the SEP system operations with the spacecraft and its potential impact on charged particle, radio waves and plasma, and other science investigations on future SEP propelled deep space missions.

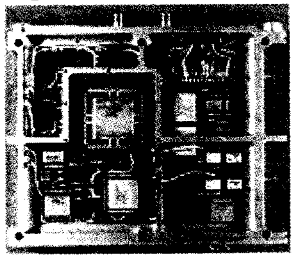
Deep Space 1

- **System Level Validation of 12 Breakthrough Technologies**

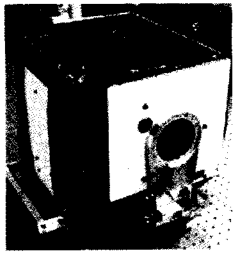




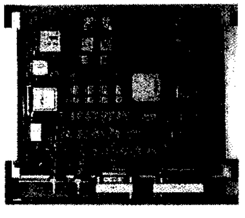
Small Deep Space Transponder



Miniature Integrated Camera Spectrometer

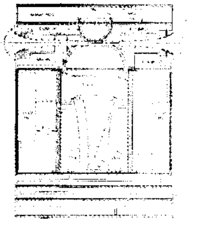


Autonomous Onboard Optical Navigation



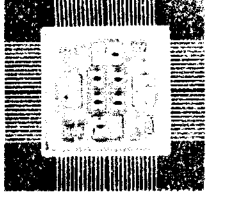
Low Power Electronics

Plasma Experiment for Planetary Exploration

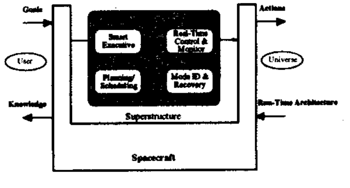


Ka-Band Solid State Power Amplifier

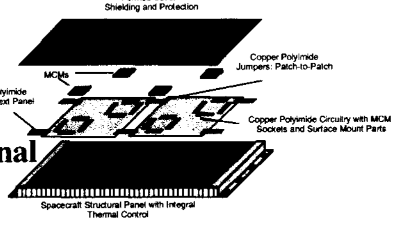
Power Activation & Switching Module

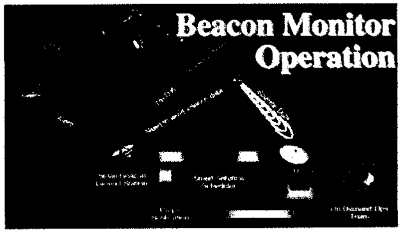


Remote Agent Architecture



Multifunctional Structure





DS1 Technology Payload

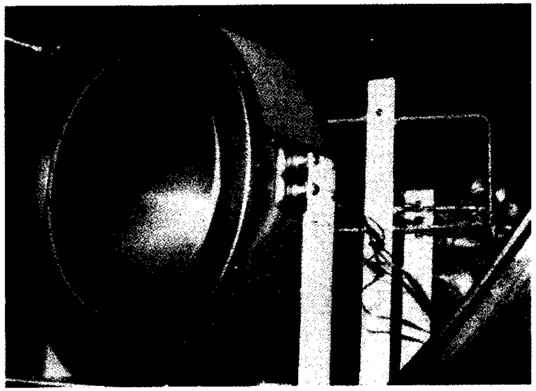
- Solar electric propulsion
  - Provided by NSTAR (NASA SEP Technology Applications and Readiness) Program
  - 2.5 kW ↔ I_{sp} = 3100 s; throttle in discrete steps to 0.5 kW ↔ I_{sp} = 1900 s
  - Diagnostics sensors for E and B, energy and density of electrons and ions, and surface contamination
- Solar concentrator array
  - Provided by BMDO
  - Arrays of cylindrical Fresnel lenses over strips of $GaInP_2$/GaAs/Ge
  - 2.5 kW at 1 AU BOL
- Miniature integrated ion and electron spectrometer
  - Energy and angle analysis for electrons and ions
  - Ion mass analysis
  - Microcalorimeter
- Miniature integrated camera and imaging spectrometer
  - 2 visible imaging channels
  - IR and UV imaging spectrometers
    - UV channel not functioning correctly
  - Shared 10-cm primary mirror

DS1 Technology Payload - Cont'd.

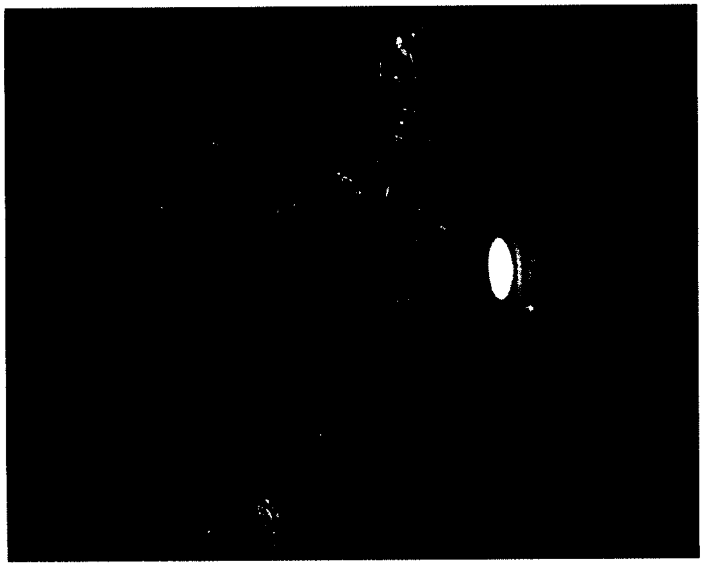
- On-board autonomy
  - Optical navigation
  - Acquisition and processing of images of asteroids against stellar background
  - Orbit determination
  - Maneuver design and execution
  - Direct commanding of IPS, MICAS, and ACS
- Remote agent
  - Planner/scheduler to generate a set of activities
  - Executive to expand that to a sequence of commands and to monitor their xecution
  - Mode identification and reconfiguration
- Beacon monitor operations
  - Transmit 1 of 4 tones to indicate urgency of request for ground action. For example
    - No tracking required
    - Track when convenient
    - Track soon
    - Track as soon as possible
- Small deep-space transponder
  - X-band receiver, X-band and K_a-band exciters, CDU, TMU, and beacon tone generator
- K_a-band solid state power amplifier
  - 2.3 W RF, 13% efficiency

DS1 Technology Payload - Cont'd.

- Power actuation and switching module
  - Power switch using high-density interconnects with mixed signal ASIC controller
- Low power electronics
  - 0.9 V logic, 0.25 μm feature size
- Multifunctional structure
  - Electronics integrated into load-bearing structural element



Ion engine operating during end-to-end test as part of DS1 STV testing



Ion Propulsion System

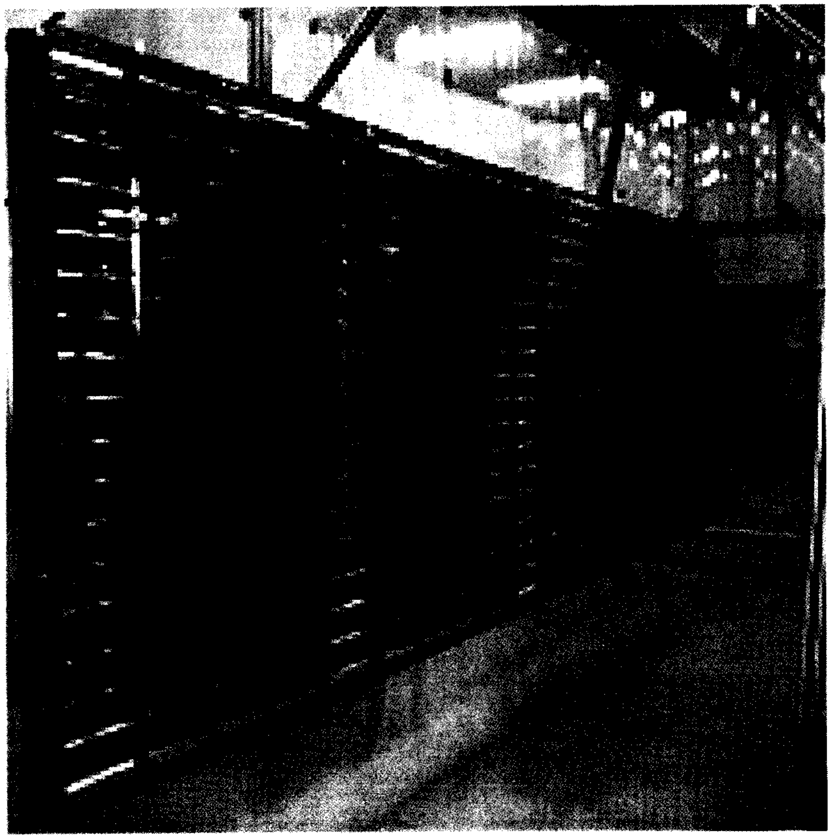
Description

- Provided by NASA SEP Technology Applications & Readiness (NSTAR) Program
- 2.5 kW $\leftrightarrow$ I_{sp} = 3100 s; throttle in discrete steps to 0.5 kW $\leftrightarrow$ I_{sp} = 1900 s.
- Diagnostics sensors for measuring interactions with spacecraft and space plasma environment

Validation

- Demonstrate high efficiency operation
  - 17.5 kg expended to reach 1 km/s as of 9/20/99. Thrust is within 2% of prelaunch prediction
- Demonstrate reliable operation for at least 200 hours
  - 2800 hours of operation achieved as of 9/20/99
- Assess effects on spacecraft operation
  - All spacecraft systems operated normally during IPS thrusting. Telecommunications conducted routinely while thrusting and through beam.

Solar Concentrator Array



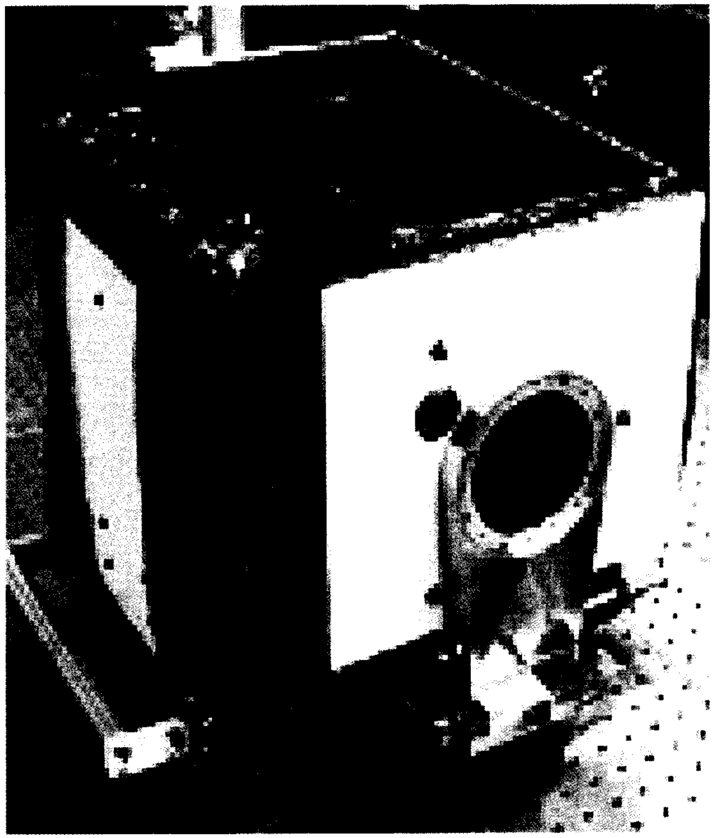
Description

- Provided by Ballistic Missile Defense Organization with support from NASA Glenn Research Center
  - Flight equipment delivered by industry
- Deployable concentrator array elements
  - Cylindrical Fresnel lenses over strips of $GaInP_2$/GaAs/Ge cells
- 2.5 kW at 1 AU (BOL)

Validation

- Demonstrate reliable deployment and stable operation
  - Alignment was so accurate, no pointing corrections were needed. Array operation stable through 11 months of flight.
- Demonstrate high efficiency power generation
  - Cells operate at 22.5% optical-to-electrical efficiency.
- Validate prelaunch models of power generation capability
  - Power generation is about 1% higher than prelaunch prediction

Miniature Integrated Camera and Imaging Spectrometer



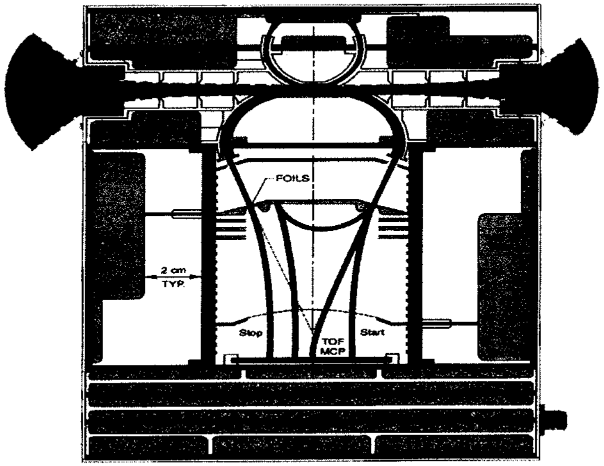
Description

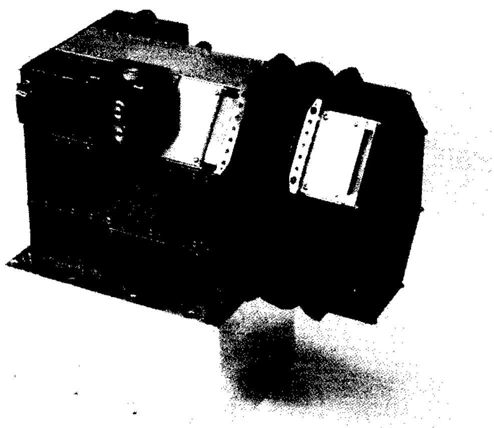
- Fully integrated camera and imaging spectrometer, developed by USGS, SSG, Inc.,University of Arizona, Boston University, Rockwell, and JPL
  - Combines four different measurement capabilities into single instrument with common optics, electronics and structure
    - Two visible imaging channels
    - IR and UV imaging spectrometers
  - Silicon carbide optics & optical bench
  - Electronically shuttered visible channel eliminates need for moving parts

Validation

- Demonstrate launch and integrity of silicon carbide bench
  - No in-flight changes in focus since final alignment before launch
- Demonstrate use of electronically shuttered visible channel (eliminating moving parts)
  - Used extensively for autonomous navigation imaging
- Demonstrate capability to return science-quality data
  - Calibrations conducted on 3 of 4 channels
  - Currently, UV channel is not working

Miniature Integrated Ion and Electron Spectrometer





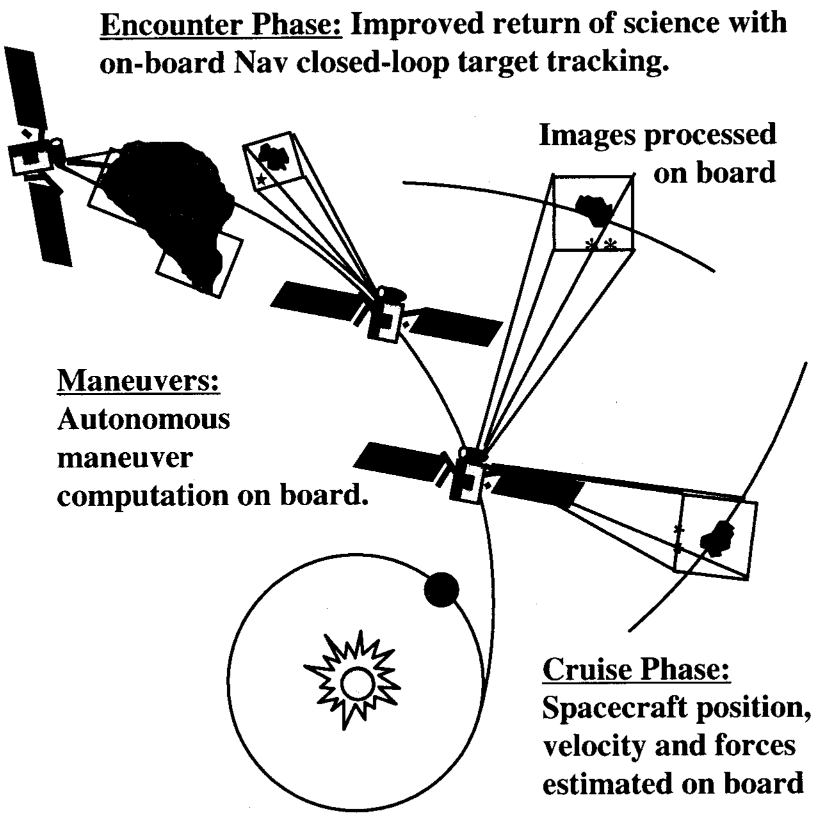
Description

- Combines multiple plasma physics instruments into one compact package
  - Energy and angle analysis for ions and electrons
  - Ion mass analysis
  - Very low power, low mass microcalorimeter

Validation

- Demonstrate ability to measure solar wind, even in presence of Xe plasma from IPS
  - Solar wind observations routinely conducted, including collaborative observations with Cassini Plasma Spectrometer

Autonomous Navigation



Description

- Integrated autonomous optical navigation and trajectory control system
  - Uses images of asteroids, stars, and target bodies for orbit determination. Designs and executes maneuvers.
  - Direct commanding of IPS, MICAS, and ACS

Validation

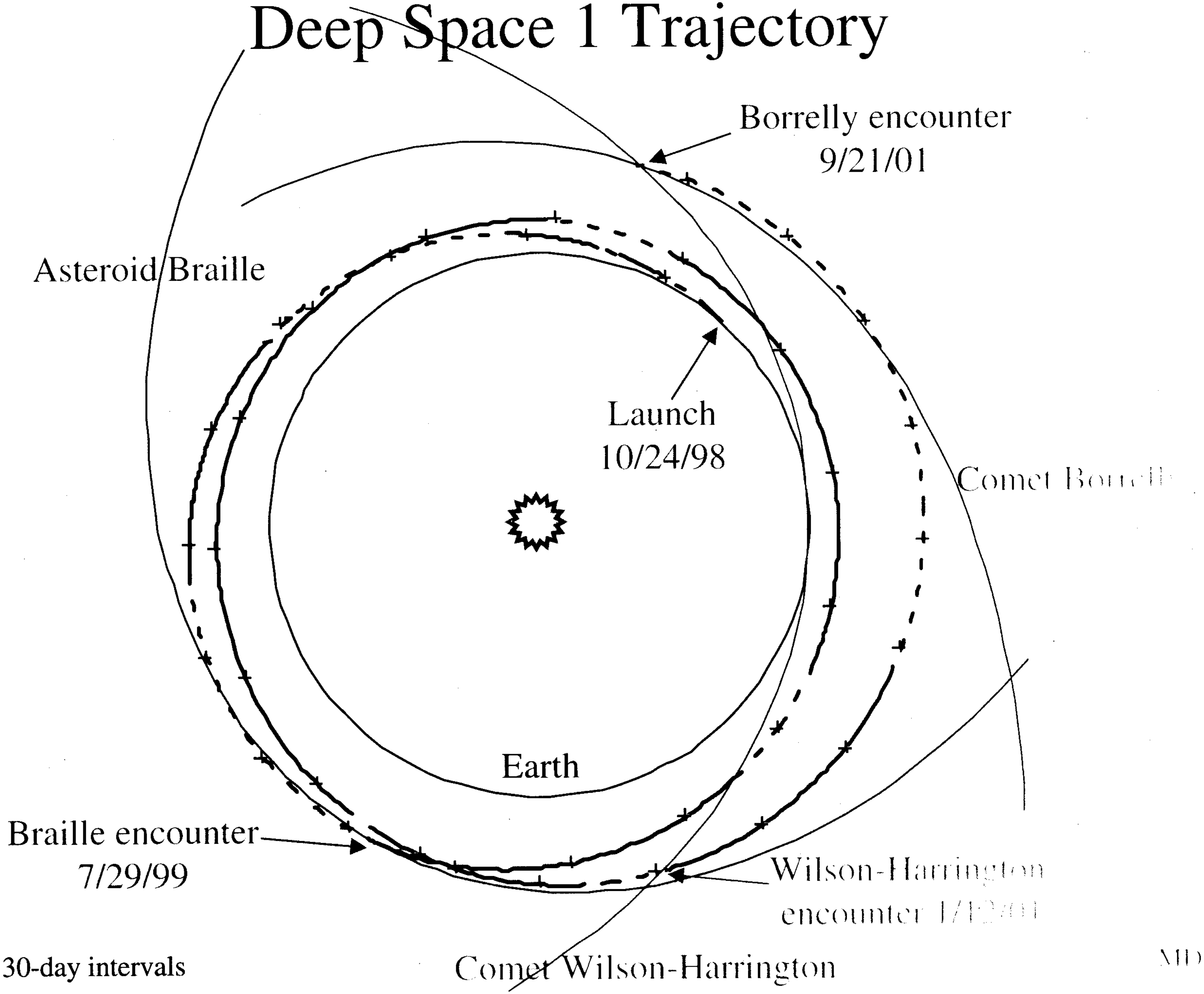
- Demonstrate autonomous picture planning and sequencing
  - Autonomously turns spacecraft and images asteroids and stars
- Demonstrate autonomous orbit determination and maneuver planning
  - Autonomously processes pictures, determines orbit (~200 km accuracy, 0.15 km/s), and updates IPS thrust profile to keep on target for asteroid encounter
- Demonstrate autonomous control of IPS thrusting
  - Autonomously commands spacecraft attitude; pressurizes, starts, and stops IPS; updates throttle level and thrust attitude regularly.

Technology Benefit Example

- Mission concept:
  - Same encounter targets as DS1 for primary and extended missions
  - Standard technologies with similar functionality:
    - N_2O_4/MMH propulsion system
    - '98-class Scaled solar array
    - Mars telecommunications system
    - Cassini-class plasma spectrometer
    - Separate visible imager and IR push-broom spectrometer

	"Standard technology" DS1	Actual DS1
Injected mass	~ 1300 kg	486 kg
Launch vehicle	Shared Atlas IIA	Shared Delta 7326

Deep Space 1 Trajectory



Time tics at 30-day intervals

MDR

Encounter Objectives and Priorities

Technology validation

- Conduct final test of autonomous navigation system
  - Represents 5% of AutoNav technology validation

Public relations

- Return one visible image of 50 pixels

Science

- Determine size, shape, geomorphology, albedo, and the minearalogy and compositional heterogeneity of the surface material. Measure, or at least constrain, the magnetization and the interaction with the solar wind, including sputtering.

Encounter Summary

- The Braille encounter was a "bonus" mission objective in addition to the primary objective of technology validation.
- For 4 days before asteroid closest approach (ACA), Braille was included among optical navigation "beacon" asteroids.
  - When Braille was found in ground analysis of AutoNav's images, it was 430 km from predicted position. Offset was 1.6 σ.
  - Using only optical data, ground designed trajectory correction maneuver (TCM).
  - AutoNav executed 3.7 m/s TCM at ACA -33 h.
  - Braille was too faint to be detected by AutoNav until ACA-17 h, when AutoNav "lock-on" to Braille.
- Out-of-range variable caused reboot and entry into "Sun standby SSA" about ACA-16 h.
  - Team conducted rapid recovery, including reactivation of MICAS and PEPE and reloading of IDS encounter software.
  - 3 optical navigation images of Braille from prior to reboot were recovered and used to design ACA-6 h TCM on ground.
  - Files were uploaded and verified, and recovery completed by ACA-7 h. All subsequent activities were sequenced.

Encounter Summary - Cont'd.

- AutoNav correctly executed ACA-6 h TCM (based on S/C acquired optical-only data-based ground design) and executed 4 optical navigation activities, all with the CCD. Last was at ACA-70 m.
- At ACA-28 m AutoNav was commanded to a different mode that allows rapid processing of APS images to update estimated location of target.
- Signal from asteroid never reached threshold, so AutoNav received no new updates on Braille's position. Apparently an unusually high noise spike did reach threshold, thus pulling pointing away from nominal.
  - Signal threshold and integration times were selected on bases of ground-based photometry of asteroid and flight experience with APS. The asteroid appeared far dimmer than expected (by factor of 5 $\rightarrow$ 10) due to unexpected camera behavior combined with the physical characteristics of Braille.
  - MICAS pointing was not correct during final approach, so most MICAS science data (after ACA-5 m) were not acquired.
  - AutoNav activated all 4 vernier movable blocks.
- All PEPE and IDS data were acquired.
- AutoNav was commanded back to normal mode shortly before ACA. After ACA spacecraft turned to point back at Braille and, with AutoNav's pointing information, acquired CCD, APS, and IR data.

DS1 Science Results Compared with DS1 Science Plan

Encounter Science Priorities	*Achieved*
Category 1.	
Partial highest resolution CCD (4 m/pixel)	No
PEPE spectra at +/- 5 sec CA	Yes
Category II	
SWIR of illuminated hemisphere	Yes
PEPE data in entire instrument region of interest	Yes
Category III	
Closup mosaic map 5-30 meter/pixel resolution	No
PEPE +/- 30 min of ACA	Yes

Summary

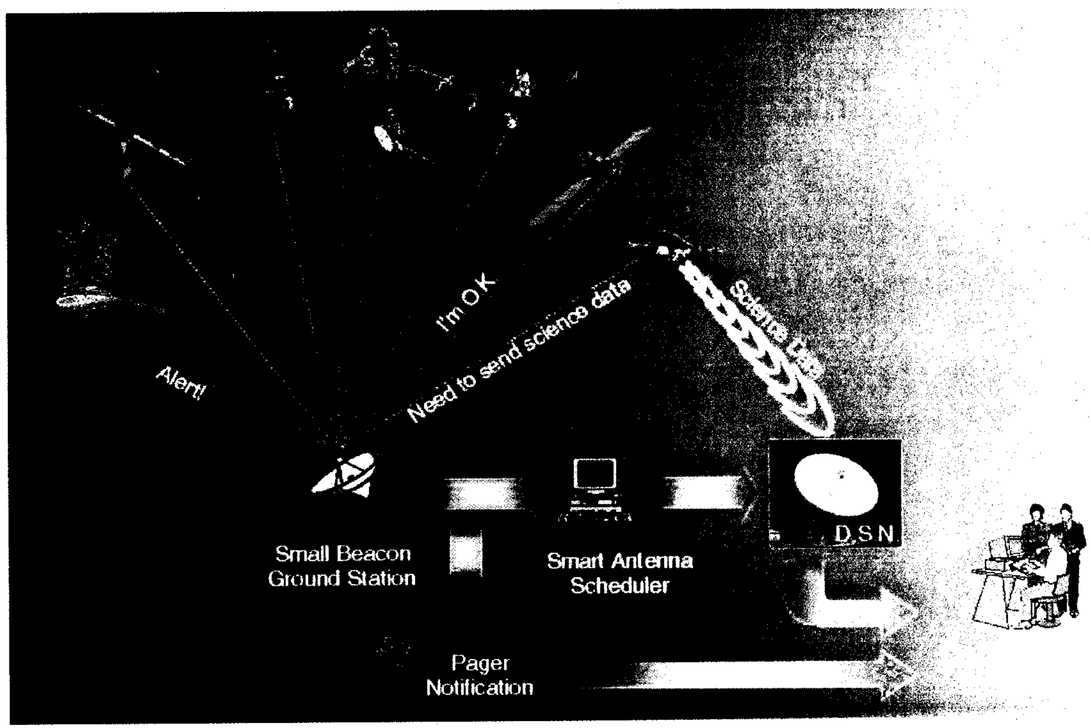
- DS1 completed its primary mission of validating tomorrow's technologies today
  - New methods of propulsion into deep space
  - New techniques of navigating through space
  - New flight equipment that makes spacecraft much smaller
  - New capabilities to make spacecraft more autonomous
- Extended mission trajectory plan provides two exciting comet flybys

Back Ups

Beacon Monitor Operations

Description

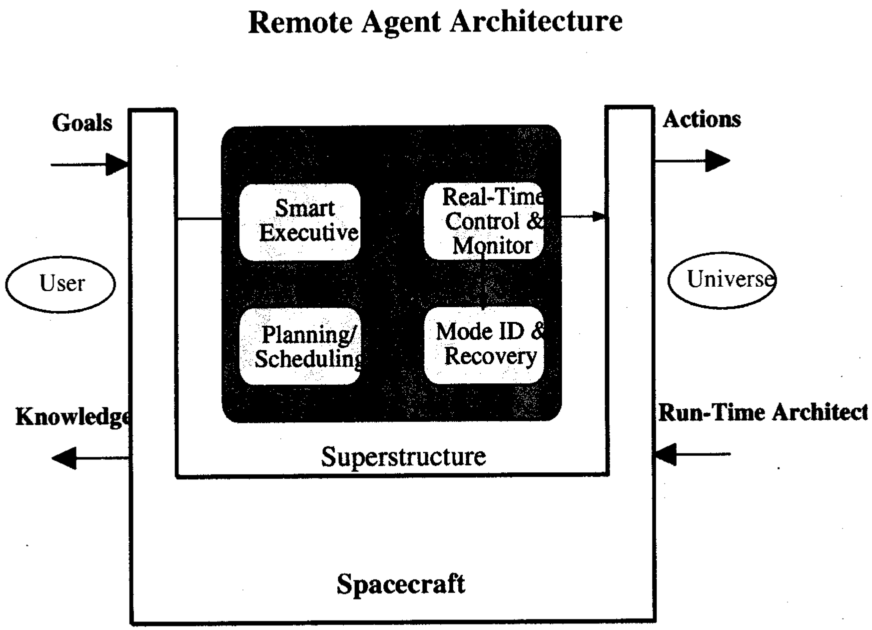
- On-board system to monitor spacecraft health and safety, and request ground action when necessary
  - On-board health and safety data summarization
  - Tone transmission to indicate urgency of ground action



Validation

- Demonstrate detectability of beacon tones
  - Beacon signals detected under variety of signal conditions
- Demonstrate data summarization
  - Spacecraft data summarized and consistent with ground analysis

Remote Agent



Description

- Autonomous "remote agent" that plans and executes on-board activities with only general direction from ground
  - Planner/scheduler to generate a set of activities
  - Executive to expand that into a sequence of commands and monitor their execution
  - Mode identification and reconfiguration to monitor spacecraft health and status

Validation

- Demonstrate on-board planning, execution, and handling of anomalies
  - Formulated and executed plans
  - Correctly handled all simulated failures, including need to replan

Telecommunications

Small Deep Space Transponder

Description

- Compact, low-mass transponder that combines multiple subassemblies into a single unit
  - X-band receiver, X- and K_a-band exciters, command detector unit, telemetry modulation unit, and beacon tone generator

Validation

- Demonstrate reliable operation for communications (X-band uplink and downlink and K_a-band downlink), ranging (X and K_a), Doppler (X and K_a), tone generation (X and K_a)
  - All functions verified through routine use and dedicated experiments. All performance consistent with prelaunch predictions

K_a-Band Solid State Power Amplifier

Description

- Highest power solid state K_a-band amplifier ever used for deep space communications
  - Generates 2.3 W output with 13% overall efficiency

Validation

- Demonstrate functionality of unit and provide K_a-band signals for DSN and for communications and radiometrics performance assessments
  - Functionality verified
  - Signals used in technology development for upgrading DSN stations for K_a-band operation.
  - Communications performance in good agreement with models. Doppler and ranging in good agreement with X-band results.

Microelectronics

Low Power Electronics

Description

- 0.9 V logic, 0.25 μm gate lengths
  - Ring oscillator, multipliers, and discrete transistors

Validation

- Demonstrate radiation-resistant low-power devices in space environment
  - In-flight performance consistent with ground tests
  - Tests repeated each week

Power Actuation and Switching Module

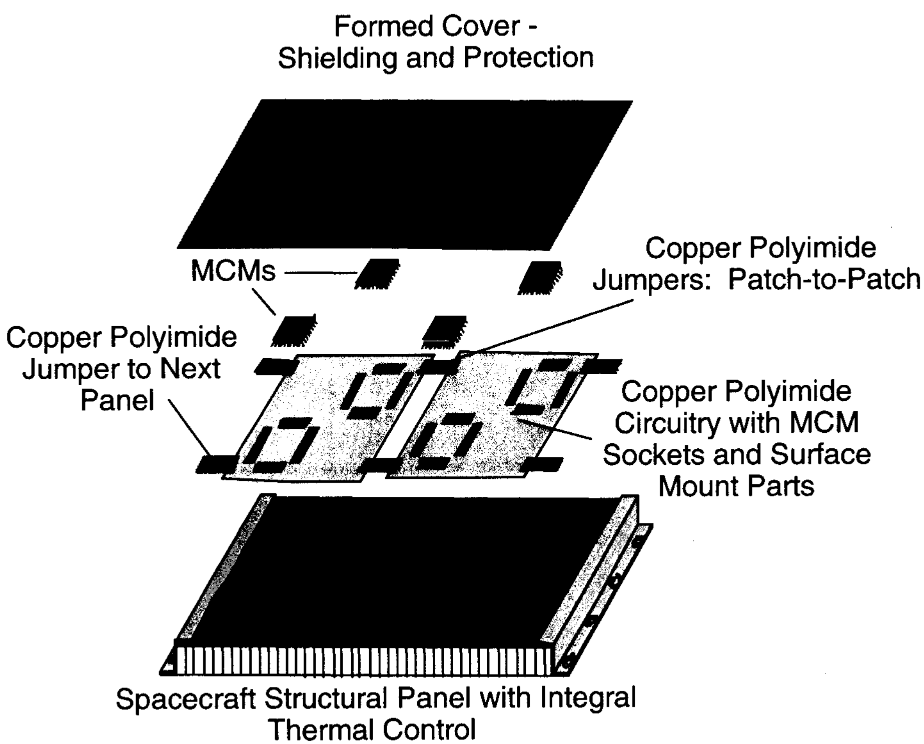
Description

- Power switch using high density interconnects with mixed signal ASIC controller

Validation

- Demonstrate operation of smart power switching and current monitoring in spacecraft power system
  - In-flight performance consistent with ground tests
  - Tests repeated each week

Multifunctional Structure



Description

- Integrates electronics into load-bearing structural element to reduce mass of spacecraft cabling and traditional chassis

Validation

- Demonstrate integration of electronics into spacecraft structure, with embedded thermal control
    - In-flight performance consistent with ground tests; no degradation observed during flight in flex connectors or multichip module sockets. Thermal gradients consistent with preflight predictions.